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Cost of solar energy generated using PV panels

Shafiqur Rehman[a,*], Maher A. Bader[a], Said A. Al-Moallem[b]

[a]Center for Engineering Research, Research Institute, King Fahd University of Petroleum and Minerals, KFUPM BOX # 767, Dhahran 31261, Saudi Arabia

[b]Design & Materials Division, Distribution Engineering Department, Saudi Electricity Company, P.O. Box 5190, Dammam 31422, Saudi Arabia

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Abstract

This paper utilizes monthly average daily global solar radiation and sunshine duration data to study the distribution of radiation and sunshine duration over Saudi Arabia. The analysis also includes the renewable energy production and economical evaluation of a 5 MW installed capacity photovoltaic based grid connected power plant for electricity generation. The study utilizes RetScreen software for energy production and economical assessment. It is found that the global solar radiation varies between a minimum of 1.63 MWh/m^2 yr^{-1} at Tabuk and a maximum of 2.56 MWh/m^2 yr^{-1} at Bisha while the mean remained as 2.06 MWh/m^2 yr^{-1}. The duration of sunshine varied between 7.4 and 9.4 h with an overall mean of 8.89 h. The specific yield was found to vary from 211.5 to 319.0 kWh/m^2 with a mean of 260.83 kWh/m^2. The renewable energy produced each year from 5 MWp installed capacity plant was varied between 8196 and 12,360 MWh while the mean remained as 10,077 MWh/yr^{-1}. The economical indicators like internal rate of return, the simple payback period, the years to positive cash flows, the net present value, the annual life cycle savings, the profitability index and the cost of renewable energy production showed that Bishah was the best site for PV based power plant development and Tabuk the worst. From environmental point of view, it was found that on an average an approximate quantity of 8182 ton of green house gases can be avoided entering into the local atmosphere each year.

Keywords: Solar radiation; Photovoltaic; Electricity; Solar energy; Renewable energy; Capacity; Sunshine duration

*Corresponding author. Tel.: +966 3 860 3802; fax: +966 3 860 3996.
E-mail address: srehman@kfupm.edu.sa (S. Rehman).
URL: http://staff.kfupm.edu.sa/ri/srehman.

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1. Introduction

It is alarming to learn that some 1.7–2.0 billion people in the world, mostly in rural areas of developing countries, have no access to electricity and further 2 billion are severely undersupplied, according to UNEP report [1]. This imbalance in energy distribution is one of the most important causes of social evil in the society. The other factors of concern to environmentalist, scientists, meteorologists, engineers and to certain extent to governments as well include the increasing global population, exponentially growing need of energy, global climatic changes and fast depleting reserves of traditional sources of energy. According the UN-sponsored intergovernmental panel on climate change projects, the global temperature will rise by up to 5.8 °C over the next century. In the present scenario, many countries have realized the need for the reduction of green house gases emission to combat the adverse global climatic change. Hence to meet the power requirements of our future generations, new clean, renewable and sustainable sources of energy should be utilized, whenever and wherever possible.

Photovoltaic (PV) technology is proven and easy to use solar of energy to generate electricity. It is being used globally to supply power to remote communities, utility peak load shaving, cathodic protection in pipelines, remotely located oil fields and gas oil separation plants (GOSPs), telecommunication towers, highway telephones and billboard, off-grid cottage/s, resorts in desert areas, water pumping for community and irrigation, municipal park lighting, exterior home lighting and many other usage.

The Kingdom of Saudi Arabia lies between latitudes 31°N and 17.5°N and longitudes 50°E and 36.6°E. The land elevation varies between 0 and 2600 m above the mean sea level. Complex terrain is found in the southwest region of the Kingdom. The East and the West coasts of the Kingdom are located on the Arabian Gulf and Red Sea, respectively. Mainly two seasons, winter and summer, are observed during the year. The vast open land experiences high intensities of solar radiation and long hours of sunshine duration. There exist a network of 40 stations where global solar radiation and sunshine duration is being recorded since 1970 and large number, more than 40, of full meteorological data collection stations where all meteorological parameters are being recorded.

For proper utilization of PV technology for energy generation, thorough and accurate knowledge of global solar radiation variation is required. In Saudi Arabia, several studies have been undertaken to understand the availability and variability of these radiation.

Rehman and Halawani [2] reviewed around 100 published papers and reports and presented a summary on the work done on solar energy in Saudi Arabia. The study revealed that a good effort has been made in all directions right from measurement to theoretical modeling and prototype model development of solar devices. The study suggested that more efficient, organized and concentrated effort should be made in the direction of solar energy devices development and utilization in Saudi Arabia. Some of the recent theoretical studies related to solar radiation prediction and understanding the behavior of the same include Refs. [3–8].

Rehman and Ghori [9] used geostatistics along with available solar radiation to estimate the radiation at locations where it is not available with fairly good accuracy. Ali et al. [10] used PV modules to supply electricity to demonstrate the working of an automated irrigation system. In order to predict the global solar radiation in time domain, Mohandes et al. used artificial neural networks and showed that radiation data can be predicted in future time domain with the knowledge of available data with acceptable accuracy [11]. Moreover, solar radiation data is also measured by the Research Institute at King Fahd University of Petroleum & Minerals, as reported by Bahel et al. [12], Kruss et al. [13], Bahel et al. [14], Srinivasan et al. [15], Bakhsh et al. [16], etc. Sabbagh et al. [17] presented an empirical formula obtained using the daily total solar radiation, sunshine duration, relative humidity, maximum temperature, latitude, altitude and the location of the place relative to the water surface. Saudi Arabia has invested a good amount of funds on the development of solar energy both on experimental and theoretical investigations. Solar energy-based appliances are being used at the Royal Commission of Yanbu and Jubail, Saudi Arabia. The world's first and the largest grid-connected PV facility was developed and tested at Solar Village situated on the outskirt of Riyadh, the capital city of Saudi Arabia [18].

Elsewhere, e.g., Libya is one of the largest oil exporting country and possesses large reserves of fossil fuel, however, it is using renewable sources of energy like wind and solar and saving its oil reserves for future use or to generate more revenues [19]. In Libya, PV technology is being used since 1976 for cathodic protection in oil pipe lines between Dahra oil field and Sedra Port, communication towers, water pumping for irrigation at El-Agailat, street and historical site lighting, etc. [19]. The total PV-installed capacity in Libya, as of May 2003, is 633.88 kWp. Furthermore, according to El Hori [19], Libya is planning to build a grid connected PV power plant with 1 MW installed capacity in the near future. PV is also being used in Jordan to pump water and in lighting the streets, schools and other governmental institutions located in remote areas. According to Hrayshat and Al-Soud [20], the total PV-installed capacity in Jordan is 82 kWp generating a total of 182.5 MWh of electricity each year.

In order to study the energy production, a PV system of 5 MWp installed capacity was considered. Monthly mean values of temperature and global solar radiation on horizontal surface along with latitude of the site were used as input in RetScreen software [21] to get the specific yield, renewable energy produced and green house gases avoided entering into the atmosphere as a result of clean energy utilization. The software also performs the economical analysis of the grid connected PV power plant in terms of internal rate of return (IRR), simple pay back period (SPP), years to positive cash flow (YPCF), net present value (NPV), annual life cycle savings (ALCS) and profitability index (PI).

Table 1
Photovoltaic module specifications

Item description	Item specification
Voltage [@ peak power] (V)	18.5
Current [@ peak power] (A)	4.86
Voltage [open circuit] (V)	22.3
Current [short circuit] (A)	5.2
Frame area (m^2)	0.63
Mounting dimensions thickness (mm)	43.5
Width (mm)	530
Length (mm)	1188
Weight (kg)	7.5
Certification	CSA, CEC

2. PV system description

The solar module or the PV part is the heart of the whole PV system. The solar module is composed of several individual PV cells connected in series or parallel. Primarily, the number of individual cells within a module and the arrangement of these cells in the module influence the energy produced by a PV module. The cells can be arranged in a module to produce a specific voltage and current to meet the particular electrical requirements. Similarly, the PV modules can be arranged to form a solar array to produce a specific voltage and the current. In the present study we have used the PV Module of 90 W peak capacity comprised of mono-Si solar cells from BP Solar/Solarex. The specifications of the module are summarized in Table 1.

The study assumes a grid connected power plant of 5 MW installed capacity comprised of 55,556 modules described in Table 1, for all the sites considered in this paper. These arrays were arranged in five units consisting of 11,111 modules each. The total PV module area covered by each unit was found to be approximately 7000 m^2. So for the whole plant the total PV modules area reached to 35,000 m^2. Inverters with a total rated capacity of 4750 kW with 95% efficiency were considered to convert DC into AC to directly feed the grid. The PV modules were assumed to be fixed, i.e. no solar tracking, and inclined at an angle equal to the site latitude and South facing. The azimuth angle was taken as zero for all the sites.

3. Results and discussion

To study the behavior of global solar radiation and sunshine duration over Saudi Arabia, the long-term overall mean values were obtained using the long-term site averages. Similarly, overall seasonal mean values of the global solar radiation and sunshine duration were obtained using monthly mean values from all the sites. The renewable energy fed to the grid at each site was obtained using RetScreen software. The detailed discussion on global solar radiation and renewable energy delivered is given in the forthcoming sub-sections.

3.1. Global solar radiation and sunshine duration behavior

It was found that Saudi Arabia experiences, on an average, more than 2.0 MWh/m^2 of global solar radiation each year on horizontal surface. The long-term mean values of sunshine duration and global solar radiation on horizontal surfaces are summarized in Table 2. Depending on geographical location, the global solar radiation varies between a

Table 2
Long-term daily mean values of sunshine duration and global solar radiation on horizontal surface

Stn #	City	Lat (deg.)	Lon (deg.)	Alt (m)	S (h)	H (MWh/m^2 yr)
1	Qurayyat	31.33	37.35	2	9.0	2.03
2	Tabarjal	30.52	38.38	3	9.0	1.72
3	Sakaka	29.97	40.20	574	9.0	1.94
4	Tabuk	28.38	36.58	773	9.1	1.64
5	Tayma	27.63	38.48	820	9.2	2.04
6	Hail	27.47	41.63	1010	9.4	1.91
7	Sarrar	26.98	48.38	75	8.7	1.66
8	Al-Ula	26.62	37.85	681	9.1	2.12
9	Qatif	26.55	50.00	8	8.4	1.73
10	Maaqala	26.37	47.37	450	8.9	1.78
11	Zilfi	26.30	44.80	605	8.9	2.04
12	Unayzah	26.07	43.98	724	9.3	2.00
13	Uqtalas-Suqur	25.83	42.18	740	9.1	2.23
14	Hutatsudair	25.53	45.62	665	9.0	2.15
15	Al-Hofuf	25.50	49.57	160	8.7	2.07
16	Shaqra	25.25	45.25	730	9.2	2.21
17	Hanakiya	24.85	40.50	840	9.1	2.21
18	Riyadh	24.57	46.72	564	9.2	1.87
19	Madina	24.52	39.58	590	9.1	2.32
20	Dawdami	24.48	44.37	0	8.8	2.17
21	Derab	24.42	46.57	0	8.7	2.26
22	Al-Kharj	24.17	47.40	430	9.1	2.03
23	Harad	24.07	49.02	300	9.0	1.71
24	Yabrin	23.32	48.95	200	9.1	2.06
25	Al-Aflat	22.28	46.73	539	9.0	2.19
26	Khulays	22.13	39.43	60	8.9	2.18
27	Sayl Kabir	21.62	40.42	1230	8.9	2.46
28	Turbah	21.40	40.45	1130	9.0	2.09
29	Taif	21.23	40.35	1530	8.9	1.98
30	Sulayyil	20.47	45.57	600	9.0	2.40
31	Bisha	20.02	42.60	1020	9.2	2.56
32	Heifa	19.87	42.53	1090	9.1	2.22
33	Juarshy	19.85	41.57	2040	8.5	1.98
34	Modaylif	19.53	41.05	53	8.5	2.32
35	Al-Numas	19.10	42.15	2600	7.4	2.21
36	Kwash	19.00	41.88	350	8.5	1.70
37	Kiyad	18.73	41.40	30	8.4	1.87
38	Sirr-Lasan	18.25	42.60	2100	8.7	1.84
39	Abha	18.22	42.48	2200	8.7	2.13
40	Najran	17.55	44.23	1250	9.1	2.53
41	Sabya	17.17	42.62	40	8.5	1.83

minimum of 1.63 $MWh/m^2 yr^{-1}$ at Tabuk and a maximum of 2.56 $MWh/m^2 yr^{-1}$ at Bisha, as seen from Table 2. It is evident from this table, that higher values of global solar radiation are observed in Nejran, Bisha, Al-Sulayyil, etc. area in the southern most part of the Kingdom and relatively lower values in the northern region like Hail, Sakaka, Tabarjal, etc. The lower values are much higher than those in other western and European countries and hence offer an opportunity to harness the power of the sun to generate electricity. The eastern and the western parts of Saudi Arabia also experience higher intensities of global solar radiations and hence should be explored.

The long-term seasonal variation of global solar radiation at 41 locations is shown in Fig. 1. From this figure, it is evident that higher values of radiation were observed during Summer months and lower in the Winter months. The seasonal variation of global solar radiation obtained using monthly mean values from 41 locations is depicted in Fig. 2. Lower values of radiations are noticed in Winter months and higher in Summer months. A maximum value of 7.09 $kWh/m^2 day^{-1}$ is found in the month of June while the minimum of 3.82 $kWh/m^2 day^{-1}$ in December. As observed from Figs. 1 and 2, the seasonal pattern of solar radiation matches with electrical load pattern prevalent in Saudi Arabia. Hence, it will prove to be advantageous to use PV technology to generate electricity for grid connected applications to meet the peak load requirements.

The long-term monthly mean values of sunshine duration for individual solar radiation stations are shown in Fig. 3. It is evident from the figure that the sunshine duration is

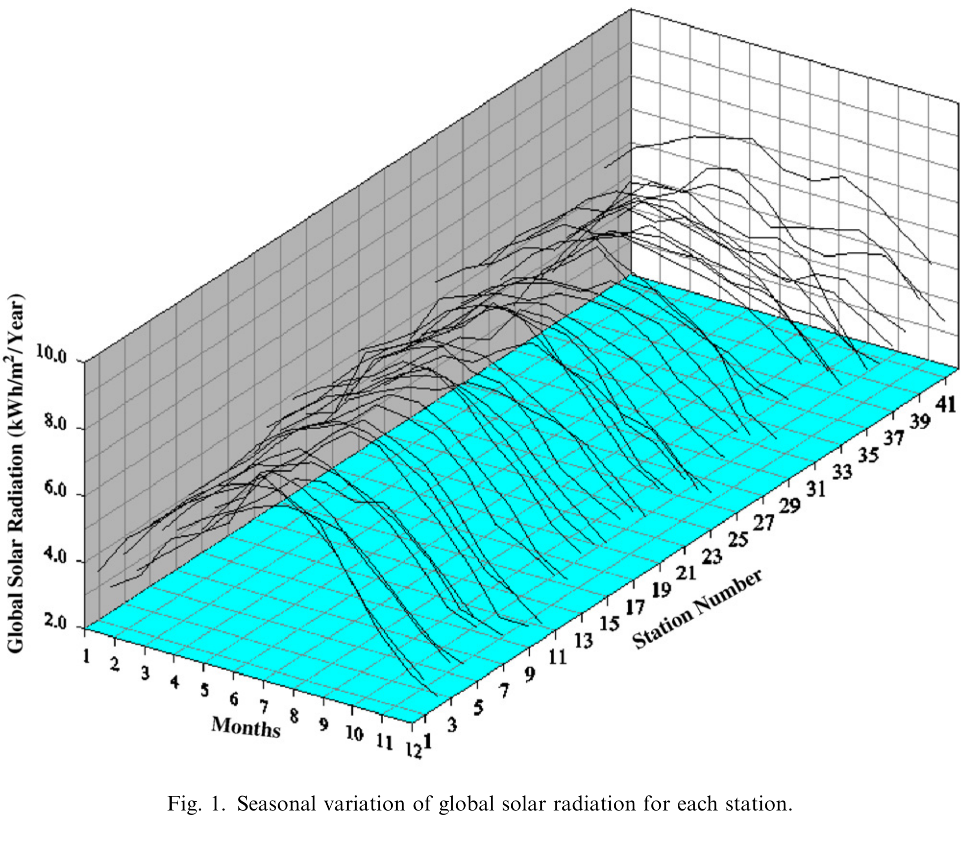


Fig. 1. Seasonal variation of global solar radiation for each station.

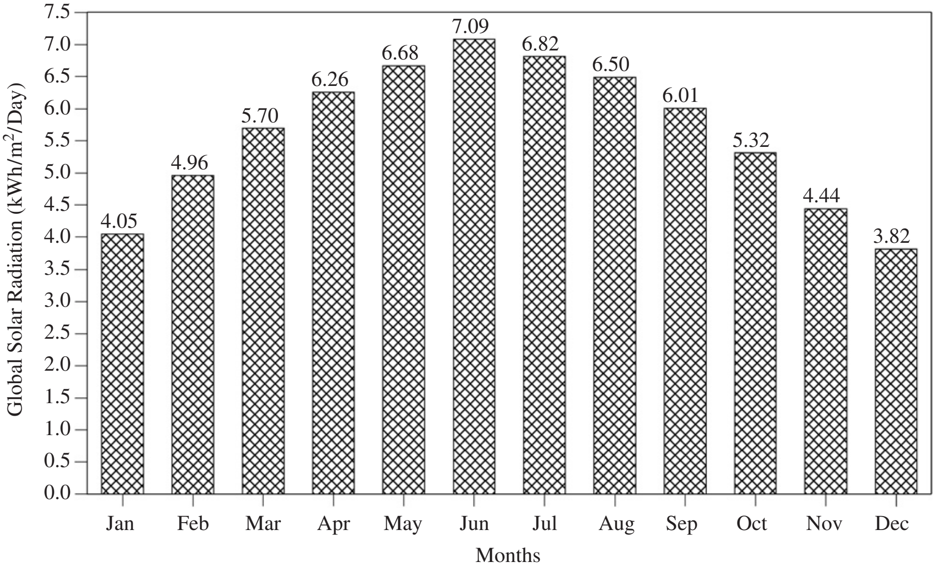


Fig. 2. Seasonal variation of global solar radiation over Saudi Arabia.

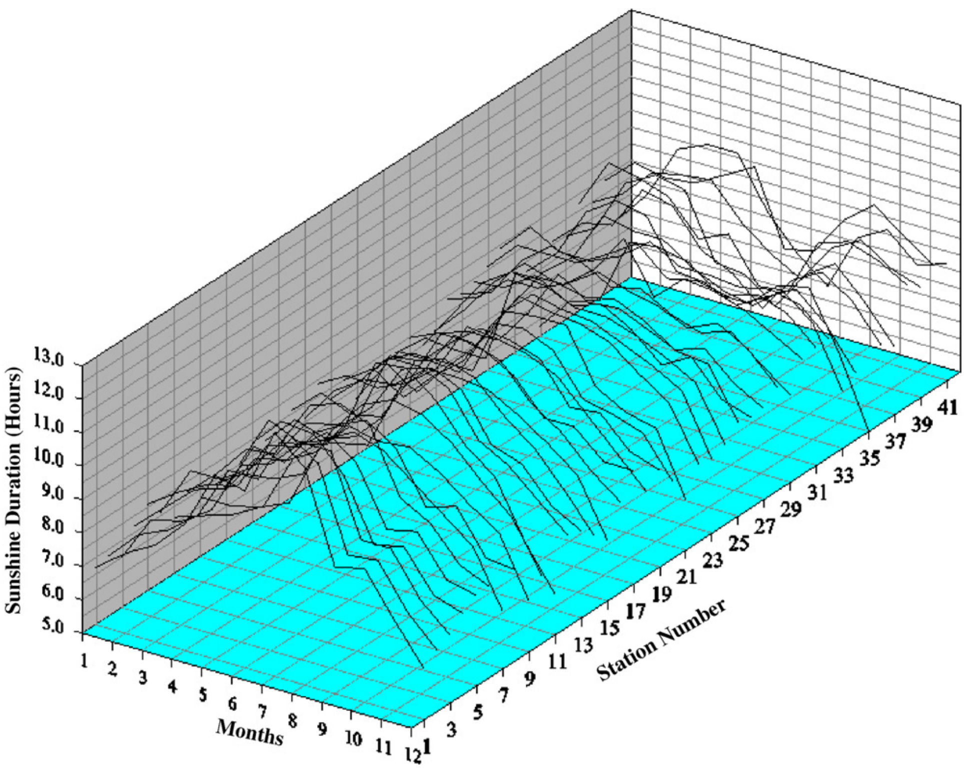


Fig. 3. Seasonal variation of available sunshine duration for each station.

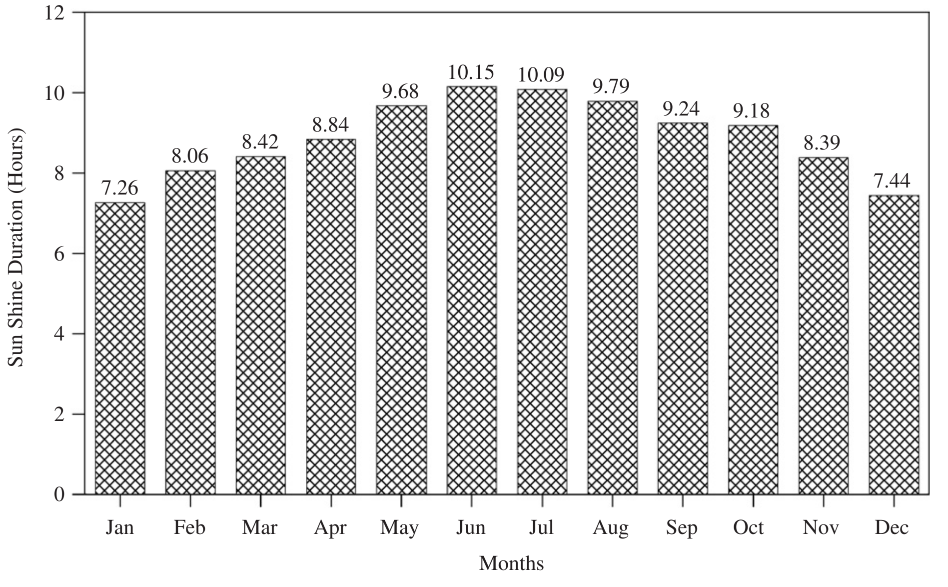


Fig. 4. Seasonal variation of sunshine duration over Saudi Arabia.

longer in Summer months and shorter in Winter months at all the locations. Fig. 4 shows the seasonal variation of sunshine duration values over Saudi Arabia obtained by averaging monthly mean values of sunshine duration from 41 locations. Longer durations of bright sunshine are observed in summertime compared to that in wintertime, as observed from Fig. 4. The overall mean value of sunshine duration, obtained by using all the values from 41 locations, was found to be 8.89 h each day and approximately 3245 h each year when multiplied by number of days in the year. As seen from Table 2, the minimum and the maximum duration of sunshine varied between 7.4 and 9.4 h corresponding to An-Numas (latitude = 19.10, longitude 42.15 and altitude = 2600 m above mean sea level) and Hail (latitude = 27.47, longitude 41.63 and altitude = 1010 m above mean sea level) regions, respectively. Higher values of sunshine duration are noticed in the northern region while relatively smaller in the southern region.

3.2. Renewable energy production

The monthly mean values of global solar radiation on horizontal surface, the monthly mean temperature, and the site latitude were used as input into the RetScreen software to obtain the specific energy yield, the renewable energy produced and the green house gases that could be avoided by the usage of the solar energy from a proposed PV based power plant of 5 MW installed capacity. Various other parameters like PV module specifications, inverter specification, etc., given in Table 1, were also used as input to the software. The model calculates the specific yield, in kWh/m^2, by dividing the renewable energy delivered by the PV system over 1 yr by the PV array area. The values of specific energy yield obtained for different locations are shown in Fig. 5. The maximum specific yield of 319.0 kWh/m^2 was obtained at Bisha while the minimum of 211.5 kWh/m^2 at Tabuk. The overall mean specific yield was observed to be 261 kWh/m^2.

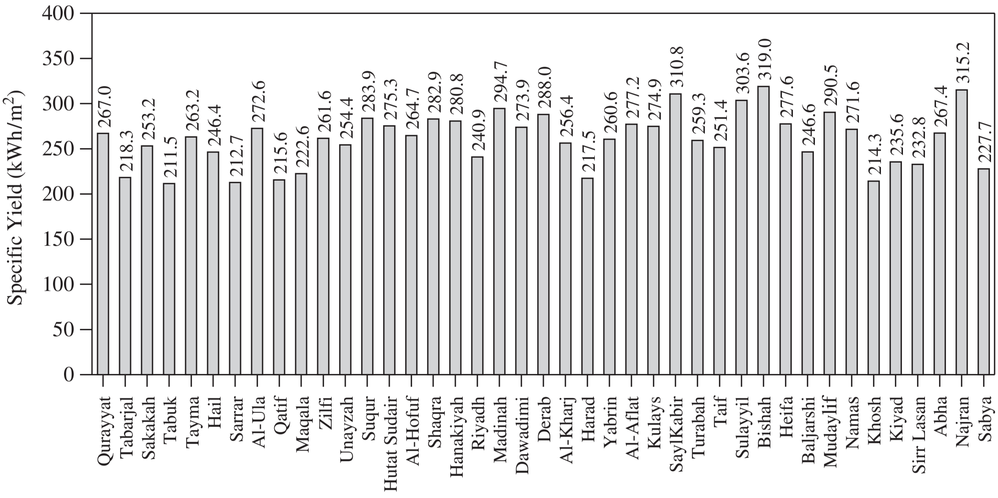


Fig. 5. Variation of specific yield for with locations.

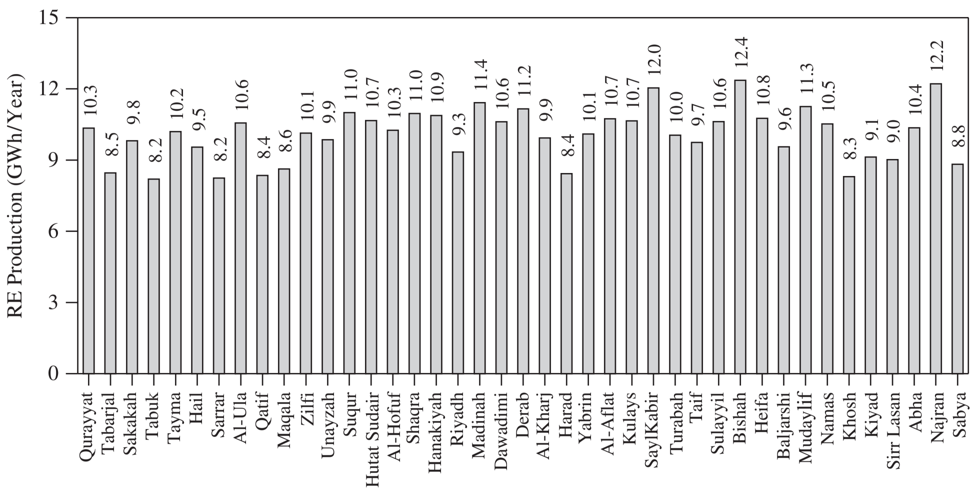


Fig. 6. Renewable energy production for different locations.

The model calculates the annual renewable energy delivered (MWh), which is the amount of equivalent DC electrical energy actually delivered by the PV system to the load, or the utility in the case of an on-grid system. The total renewable energy produced in a year from 5 MW PV power plants at all the 41 locations is shown in Fig. 6. The maximum annual energy production of 12.4 GWh was obtained from Bishah power plant while the minimum of 8.2 GWh from Tabuk and Sarrar power plants. The respective power plant efficiencies were 28.3% and 18.7%. On an average, 10.0 GWh of electricity with an

approximate efficiency of 23% can be produced each year in any part of Saudi Arabia from a PV power plant of 5 MW installed capacity.

3.3. Economical feasibility analysis

The RetScreen software, capable of performing the economical feasibility analysis of hybrid, stand alone and grid connected renewable energy systems, was used to find out the IRR, SPP, YPCF, ALCS, NPV, PI and the cost of energy (COE) per kWh of electricity produced. The input economical parameters such as energy cost escalation rate, inflation rate, etc are summarized in Table 3. The costs of major elements of the PV power plant, taken from the literature, are given in Table 4. The major chunk of the fund about 70% accounts for renewable energy equipment such as PV panels, its transportation and installation, etc. The other major head where the money consumed is the balance of plant cost that accounts for about 28% of the total costs. All of these costs and interest rates given in Tables 3 and 4 were used as input to the RetScreen software for economical feasibility analysis of all the sites.

The development of a PV project would be acceptable if IRR is equal to or greater than the required rate of return. It is calculated by finding the discount rate that causes the net present value of the project to be equal to zero. The IRR calculated for all the locations is shown in Fig. 7b. As seen from this figure, the IRR increases directly with the increase in global solar radiation value, Fig. 7a. The maximum IRR of 16.7% is found at Bisha while the minimum of 10.7% at Tabuk. In Saudi Arabia, using assumed input data given Tables 3 and 4 an IRR of 13.5% can be achieved at any location.

Table 3
Summary of various interest rates used in the economical feasibility study

Item description	Value
Energy cost escalation rate	4%
Inflation rate	2.5%
Discount rate	5%
Avoided cost of energy	0.5 $/kWh
Project life	25 yr

Table 4
Initial cost of PV power plant

Item description	Cost (US $)	% Of total cost
Feasibility study	80,000	0.2%
Development cost	70,000	0.2%
Engineering cost	62,500	0.2%
RE equipment	27,750,000	69.6%
Balance of plant cost	11,094,003	27.8%
Miscellaneous	806,130	2%
Total initial cost	39,864,634	100%
Inverter replacement cost	1,000,000	Every 5 yr
Operation and maintenance	334,500	Annual

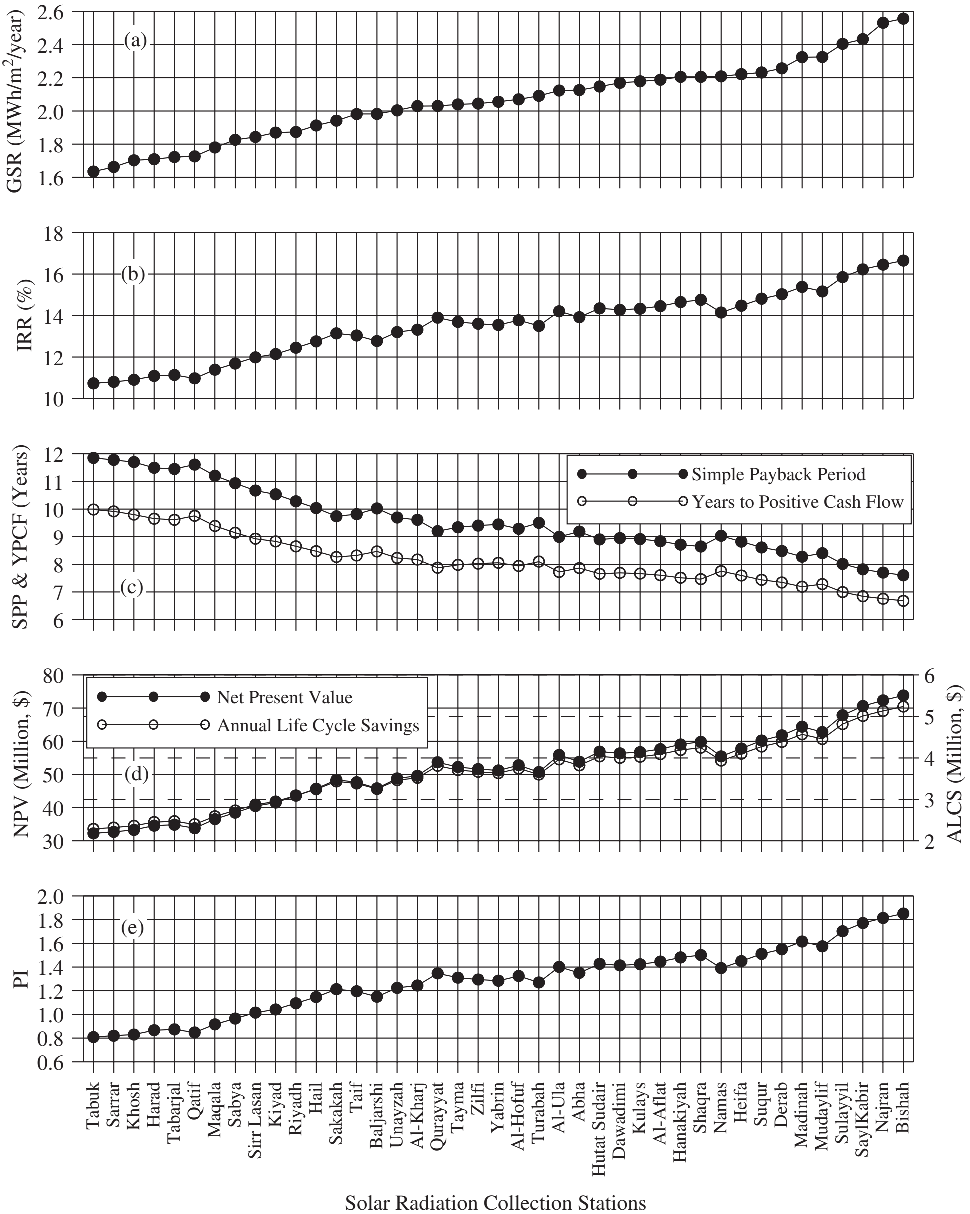


Fig. 7. Variation of economical indicators with locations.

The model calculates the SPP, which represents the length of time that it takes for an investment project to recoup its own initial cost, out of the cash receipts it generates. The model uses the total initial costs, the total annual costs (excluding debt payments) and the total annual savings, in order to calculate the SPP. The model uses the year number and the cumulative after-tax cash flows in order to calculate the YPCF. The number of YPCF represents the length of time that it takes for the owner of such a project to recoup its own



Fig. 8. Cost of energy (COE).

initial investment out of the project cash flows generated. Both of these parameters i.e. SPP and YPCF are shown in Fig. 7c for all the locations. Minimum values of both SPP and YPCF of 7.6 and 6.7 yr, respectively, were found for Bisha. The corresponding maximum values of 11.9 and 10 yr were found at Tabuk. On an average, the SPP and YPCF can be achieved in 9.6 and 8.2 yr at any location, respectively.

In NPV analysis, the present value of all cash inflows is compared with the present value of all cash outflows associated with an investment project. The difference between the present values of these cash flows, called the NPV, determines whether the project is generally an acceptable investment or not. Positive NPV values are an indicator of a potentially feasible project. The PI is calculated as the ratio of the NPV over the project equity. Positive ratios are indicative of profitable projects. The ALCS is the levelized nominal yearly savings having exactly the same life and net present value as the project. The ALCS are calculated using the net present value, the discount rate and the project life. The NPV and ALCS are shown in Fig. 7d while PI in Fig. 7e.

The model calculates the renewable energy production cost or COE. It is defined as the avoided cost of energy required for the project to break-even. The COE is calculated assuming that all financial parameters other than the avoided cost of energy are kept constant. The COE was calculated for all the location using RetScreen model and is shown in Fig. 8. The COE varies between a minimum of 20 and a maximum of 30 cent/kWh, as seen from Fig. 8. On an average, in Saudi Arabia, each kWh of renewable energy can be produced at a cost of 25 cent.

3.4. Green house gases

The amount of green house gases which could be avoided as a result of usage of 5 MW power plants at these locations is plotted in Fig. 9. From this analysis it was observed that a total of 335,455 ton of green house gases could be avoided entering into local

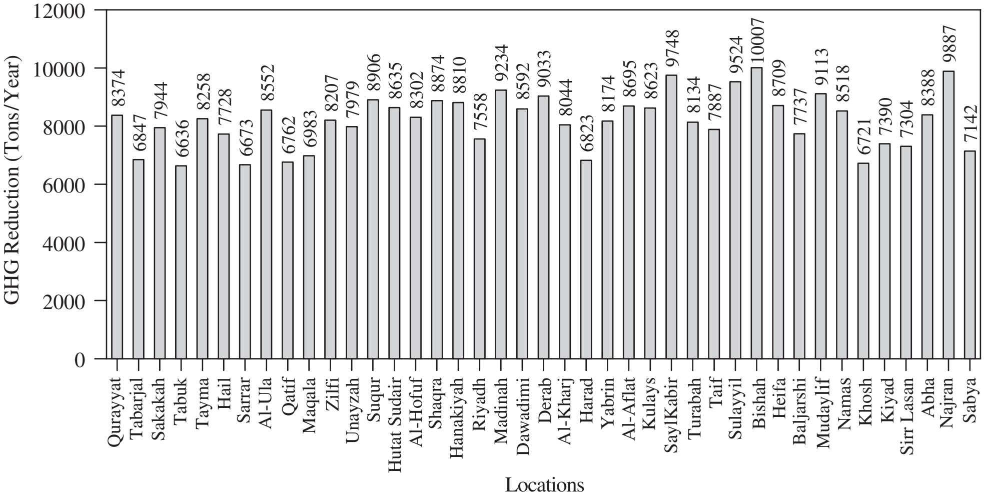


Fig. 9. Green house gases reduction due usage of PV systems for different locations.

atmosphere each year if 41 power plants each of 5 MW capacity are installed in Saudi Arabia. On an average 914 ton of green house gases each year can be avoided from entering into atmosphere from any location in the Kingdom from a 5 MW capacity PV power plant.

4. Conclusions

The study throws light on the following points:

- The global solar radiation varies between a minimum of 1.63 $MWh/m^2 yr^{-1}$ at Tabuk and a maximum of 2.56 $MWh/m^2 yr^{-1}$ at Bisha while mean value remained as 2.06 $MWh/m^2 yr^{-1}$.
- The duration of sunshine varied between 7.4 and 9.4 h with an overall mean of 8.89 h or about a total of 3245 h in a year.
- The specific yield was found to vary from 211.5 to 319.0 kWh/m^2 with a mean of 260.83 kWh/m^2.
- The renewable energy produced each year from 5 MWp installed capacity plant was found to vary between 8196 and 12,360 MWh while the mean remained as 10,077 MWh/yr.
- The mean value of internal rate of return IRR was found to be 13.53% while the minimum and maximum varied between a minimum of 10.73% and a maximum of 16.65%.
- The SPP varied between 7.6 and 11.8 yr while YPCF between 6.7 and 10. The mean values of SPP and YPCF were found to be 9.6 and 8.2 yr, respectively.
- The NPV was found to vary between $32 and $74 millions while the mean value remained as $51.3 million.
- The PI varied between 0.81 and 1.85 while the mean was found to be 1.287.
- Based on economical indicators, Bishah was found to be the best site for the development of PV based power plant and Tabuk the worst.

- From environmental point of view, it was found that on an average an approximate quantity of 8182 ton of green house gases can be avoided entering into the local atmosphere each year from a 5 MW capacity PV plant in any part of the Kingdom.
- The electricity demand patterns in Saudi Arabia matches with the pattern of global solar radiation intensity and sunshine duration. Hence this favors the usage of PV based electricity generation to meet the peak load requirements in summer time and day light hours throughout the year.
- It is recommended that more detailed techno-economical feasibility study must be conducted for Bishah site and a pilot plant should be developed there and monitored to overcome the various aspects of technology transfer and adoption in Saudi Arabia. This will also help in studying the engineering performance of such a power plant in local environment.

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